Increasing the fatigue strength of welded structural details in corrosive environments by applying high frequency mechanical impact treatment

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corrosion, fatigue strengths, high frequency mechanical impact treatment

The fatigue strengths of certain structural details can be raised significantly by utilising high frequency mechanical impact treatment (HFMI) procedures on welded structures. The application of HFMI procedures on offshore structures could thus lead to structures with substantially greater economic viabilities. However, investigations have not yet been conducted concerning efficiencies of the procedures in corrosive environments. The latest results from investigations on corroded structural details with the S355 material show that, even in extremely corrosive environments, the fatigue strength in comparison with the untreated notch cases can be increased by means of the HFMI post-weld treatment. Based on this test data, S-N curves and FAT classes were elaborated for the structural details of HFMI-treated butt welds and transverse attachments in corrosive environments. These are presented in this article.

1 Motivation and objectives

Support structures of offshore wind turbines (OWT) are designed for a service life of at least 20 years [1]. Their components are subjected to severe fatigue loads from wind, waves and turbine operation. Therefore, fatigue strength of the welded joints is predominant during the design of these components (e.g. plate thickness). The post treatment of the weldments with the high frequency mechanical impact (HFMI) enables a more economical design. Currently, the application of HFMI on offshore structures is not permitted due to a lack of standardisation and queries from the drafting committees of design norms regarding the influence of the corrosive environment on the effectiveness of the process. In order to enable the consideration of HFMI in design norms for the case of free corrosion by seawater, investigations on the fatigue strength HFMI enhancement under corrosive conditions are necessary. For this reason, investigations were carried out on welded and HFMI-treated steel specimens under the influence of corrosion within the framework of a joint research project of the authors [2]. Based on these investigations, design recommendations were developed.

A comprehensive correlation of the applied laboratory corrosion methods with real marine corrosion was carried out and it was published in [3] along with the experimental results of fatigue tests on butt welds in the untreated (as-welded - AW), corroded state. Evaluation of the experimental results based on the estimation of the S-N curves with a fixed slope was performed in [4] for both in the AW and the HFMI-treated condition. The characteristic fatigue strengths were determined based on the nominal as well as on the notch stress approach and were specifically discussed in regard to the corresponding FAT classes recommended by the IIW [5; 6]. A full report of the test results is provided in [2].

The present study is an English version of the article that appeared in the journal "Schweißen und Schneiden" in 2018 [7] and focuses on the final design recommendations derived for the two investigated HFMI-treated joints, the butt weld and the transverse non-load-carrying attachment. These recommendations are compared with the respective norms and regulations.

2 HFMI post-weld treatment: Mode of action and design rules

The high frequency mechanical impact is a mechanical post-weld treatment method. Therewith, the notch effect of the weld toe is reduced, the surface layer is hardened, and compressive residual stresses are introduced in the treatment area. As a result, the load stresses superpose with the generated compressive residual stresses, resulting in compressive mean stresses. These effects lead to delayed crack initiation and a reduction of the crack growth rate. Consequently, the service life is extended, and the fatigue resistance of the treated structural detail is increased [8; 9]. Based on extensive experimental investigations carried out in recent years, design recommendations have been developed for the consideration of these effects. An overview of these investigations was compiled in [10] and a design concept was derived based on the large database. In particular and with regard to [10], a guideline for HFMI-treated welds [6] was developed and published by the IIW (International Institute of Welding). This guideline enables the consideration of the fatigue strength increase through the application of HFMI in the design process. The respective FAT class of the untreated structural detail is upgraded depending on the nominal yield strength of the treated material and under consideration of the stress ratio.

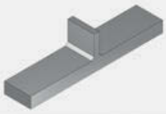
Structural detail	Condition	FAT class according to rules and regulations with corresponding slope m specification of reference values for $N_c = 2 \cdot 10^6$ cycles			
		IIW AW [5], HFMI [6] (no corrosion)	EC3 [11] (no corrosion)	DNV GL [12] (no corrosion)	DNV GL [12] (free corrosion)
Butt weld 	AW	90 m = 3	90 m = 3	90 m = 3	63 m = 3
	HFMI	160 m = 5	-	-	-
Transverse attachment 	AW	80 m = 3	80 m = 3	80 m = 3	56 m = 3
	HFMI	140 m = 5	-	-	-

Table 1 • FAT classes for the structural details butt weld and transverse attachment in the as-welded (AW) and the HFMI-treated (HFMI) condition according to IIW [5; 6], EC3 [11] and DNV-GL-RP-C203 [12].

Table 2 • Mechanical properties of the material S355J2+N (values are taken from the inspection certificates of the manufacturers [2]).

Structural detail	Plate thickness	Upper yield strength	Tensile strength
Butt weld	t = 15 mm	R_{eH} = 469 MPa (mean)	R_m = 566 MPa (mean)
Transverse attachment	t = 25 mm	R_{eH} = 369 MPa	R_m = 549 MPa

Table 3 • Chemical compositions (melt analysis) of the material S355J2+N (values are taken from the inspection certificates of the manufacturers [2]).

Chemical element	C	Si	Mn	Cr	Ni	S	P	Cu	N	Al	Mo	V	Al-T
S355J2+N max values acc. [13]	0.200	0.550	1.60	-	-	0.0250	0.025	0.550	-	-	-	-	-
S355J2+N t = 15 mm (mean) [2]	0.155	0.229	1.42	0.032	0.017	0.0037	0.009	0.014	0.0043	0.035	0.004	0.002	-
S355J2+N t = 15 mm [2]	0.162	0.534	1.56	0.041	0.024	0.0007	0.012	0.028	-	0.02	0.011	0.001	0.045

The slope m of the S-N curve of HFMI-treated welds is set to 5 for up to 10^7 cycles. Table 1 gives an overview of FAT classes according to various design standards for the butt weld and transverse non-load-carrying attachment structural details, which were examined in the present study. Based on the IIW recommendations for the fatigue design of welded joints [5], the European standard EN 1993-1-9 (EC3) [11] and the guideline DNV-GL-RP-C203 [12] for offshore structures, the untreated butt welds are assigned to FAT 90. The transverse attachments in the as-welded condition are classified as FAT 80. The slope of the S-N curve corresponds to m = 3 in both cases.

The current regulations of EC3 [11] and DNV GL [12] do not provide any specifications for the design of HFMI-treated welded joints. As described above, the IIW allows the consideration of the HFMI treatment [6] during the design phase. For instance, the FAT class can be upgraded by five categories using the material S355. This results to an applied FAT 160 for the HFMI-treated butt welds and a FAT 140 for the HFMI transverse attachments respectively, each with the corresponding slope of m = 5 for the S-N curve. Due to a lack of investigations on the influence of corrosion, current rules do not contain any specifications for the use of HFMI-treated welds in corrosive environments. For the application of as-welded joints with free corrosion, i.e. without any corrosion protection, DNV GL provides design specifications in DNVGL-RP-C203 [12] depending on the structural detail. In the case of free corrosion, FAT classes with reduced fatigue strength values are proposed for the fatigue assessment. For butt welds, this results in a classification in FAT 63. For the transverse attachments, FAT class 56 has to be assumed respectively. This corresponds to a reduction by three FAT classes or a reduction to 70% of the fatigue strength compared to the same detail under normal atmospheric conditions. The slope of the S-N curve is assumed throughout the fatigue life to be equal to 3 (m = 3), exhibiting no knee point in the high cycle regime.

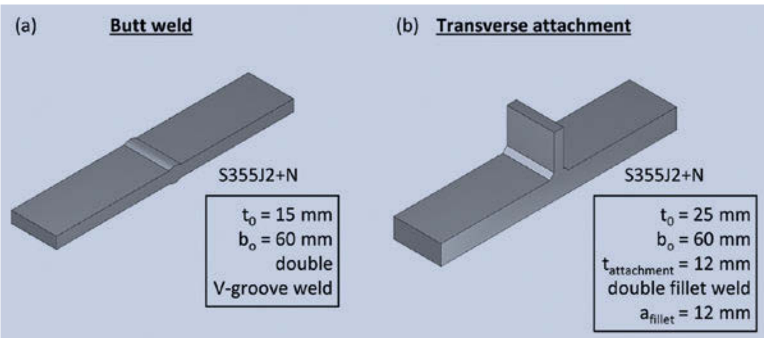


Fig. 1 • Investigated specimens of the structural details butt weld (a) and transverse attachment (b)

3 Experimental investigations in corrosive environments

3.1 Testing procedure

In order to investigate the influence of a corrosive environment on the fatigue behaviour of as-welded and HFMI-treated welds, fatigue tests were performed on corroded specimens under dry conditions and in seawater. All specimens were tested using a stress ratio of R = 0.1. For the evaluation of the crack behaviour during crack formation and crack growth individually, two methods (Sections 3.3 and 3.4) were defined for the pre-corrosion of the specimens and the subsequent tests. Both pre-corrosion methods resulted in an average loss of plate thickness of comparable magnitude ($\Delta d \leqslant 0.1$ mm). Applied laboratory methodology is described more detailed in [2]. Furthermore, the corrosion behaviour of the laboratory specimens is as well compared with test specimens that were exposed to real marine corrosion in [3].

3.2 Test specimens and materials

Butt welds and transverse non-load-carrying attachments were investigated as mentioned above. The tests were carried out on as-welded and HFMI-treated specimens of mild steel S355J2+N (material number: 1.0570). The mechanical properties and the chemical composition of the investigated material can be found in Table 2 and Table 3 respectively. The specimens and the dimensions of their test cross section are illustrated in Fig. 1.

3.3 Fatigue tests after corrosion in the salt spray chamber (SSC)

For the simulation of the corrosion influence on the crack formation, the salt spray chamber test was performed by the Karlsruhe Institute of Technology according to ISO 9277 [14]. The specimens were corroded in the SSC for a duration of 240 h in order to simulate a marine corrosive environment, see Fig. 2a. After pre-corrosion, the specimens were tested subsequently at dry, laboratory-air conditions. The fatigue tests were carried out under cyclic axial tensile load (ax) as well as under cyclic 4-point bending load (b).

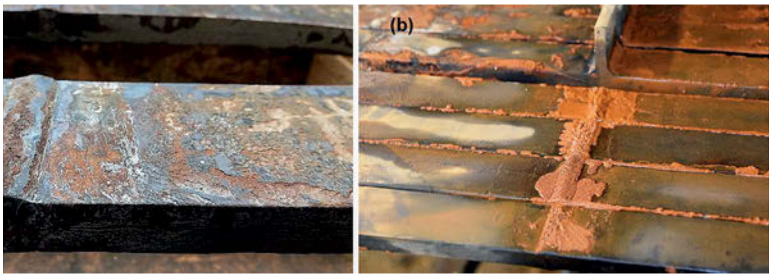


Fig. 2 • Specimens after pre-corrosion by salt spray (a) or by artificial seawater (b).

Fig. 3 • Test setup for the fatigue tests in artificial seawater.

3.4 Fatigue tests in artificial seawater (ASW)

Fatigue tests were performed in artificial seawater at the University of Applied Sciences Munich, in order to investigate the influence of corrosion on both the crack initiation and the crack growth behaviour. Prior to fatigue tests, the specimens were pre-corroded by exposing them to artificial seawater with oxygen saturation according to ASTM D1141 – 98 [15] for a duration of 30 days (see Fig. 2b). After pre-corrosion the fatigue tests were carried out in the ASW under cyclic 4-point bending load (see Fig. 3). The parameters (temperature, pH value, salt content, oxygen saturation) of the artificial seawater were observed and readjusted with the help of a previously validated monitoring system. The upper limit of the test frequency was 1 Hz. Hence, sufficient exposure of the specimens in the corrosive medium after the formation of macrocracks was ensured. Therewith, the influence of corrosive medium on crack growth could be documented as well. Moreover, as shown by Oberparleiter in [16], the influence of the test frequency in this range on the estimated fatigue strength is negligible, especially if the crack formation phase represents a significant part of the fatigue life, as in the case of HFMI-treated welds [17].

3.5 Test results

The fatigue tests were carried out up to failure in the weld toe or the parent metal. By measuring the fracture patterns, fatigue fracture areas of approximately 50 to 60% of the initial cross section of the specimens were documented. The fatigue strength was determined according to DIN EN 1993-1-9 [11] using the prediction interval approach as it was presented in [18]. According to the IIW guideline for HFMI-treated welded joints [6], the fixed slope with m = 5 was used for the S-N curve up to 10^7 cycles. Table 4 presents the calculated values for the mean ($\Delta\sigma_{50\%}$) and characteristic fatigue strength $\Delta\sigma_{c,95\%}$), which refers to the fatigue strength at $2 \cdot 10^6$ cycles.

4 Development of design recommendations

4.1 Evaluation procedure

Design FAT curves were derived considering the loading type and the corrosion type based on the fatigue strength, which was estimated from the implemented experimental investigations. The loading type can affect the fatigue strength of welded structural details; under bending, a linear stress gradient arises through the thickness of the cross-section, with a positive effect on fatigue strength. For this purpose, the British Standard BS 7608 [19] introduces the correction factor k_{tb}. This factor can be applied in order to consider this positive effect of bending. Maddox stated in [20] that the influence of the loading condition has to be considered explicitly during the evaluation of the average fatigue strength and allows the derivation of an improvement factor. However, due to a larger scatter of the results under bending stress, this effect is generally smaller when considering the characteristic fatigue strength and by using the fixed slope for the evaluation of the results. This aspect was taken into account when deriving the design values based on the presented results for the respective structural details.

Table 4 • Fatigue strength values of test series on HFMI-treated structural details considering the influence of corrosive environment.

Structural detail	Series	m_{fix} [-]	$\Delta\sigma_{50\%}$ [MPa]	$\Delta\sigma_{c,95\%}$ [MPa]
Butt weld	BW_HFMI_SSC_ax	5	224	182
	BW_HFMI_SSC_b	5	270	237
	BW_HFMI_ASW_b	5	240	214
Transverse attachment	TA_HFMI_SSC_ax	5	182	134
	TA_HFMI_SSC_b	5	208	*108*
	TA_HFMI_ASW_b	5	175	130

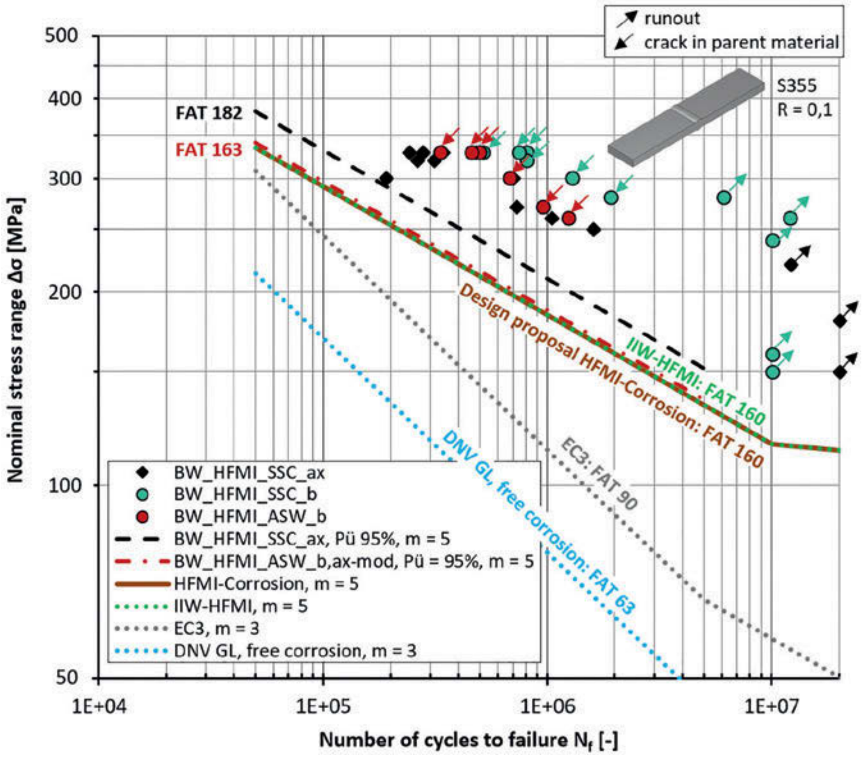


Fig. 4 • Design proposal for HFMI-treated butt welds in corrosive environment, R = 0.1, S355J2+N, comparison with design curves according to IIW-HFMI [6], EC3 [11] and DNV GL [12].

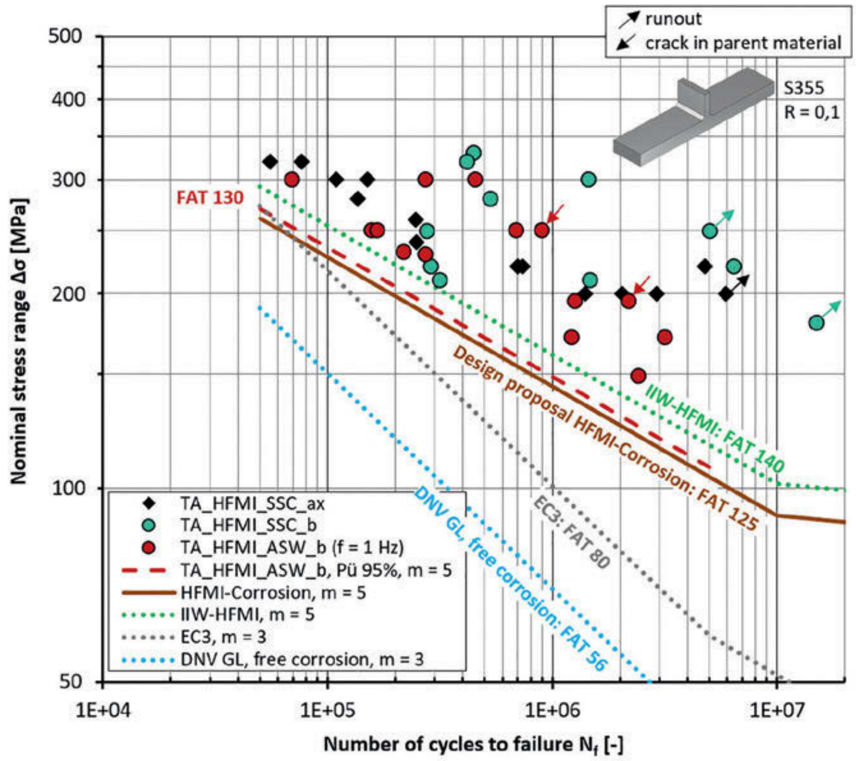


Fig. 5 • Design proposal for HFMI-treated transverse attachments in corrosive environment, R = 0.1, S355J2+N, comparison with design curves according to IIW-HFMI [6], EC3 [11] and DNV GL [12].

Geometric measurements of the butt weld specimens showed that negligible linear and angular misalignments occurred. Consequently, the stress levels of the specimens tested under axial tensile load were not increased in order to follow a conservative design approach.

The calculated S-N curves are presented in the following sections 4.2 and 4.3 for the butt welds and transverse attachments respectively. Downwards arrows in the diagrams indicate failures due to crack initiation in the parent material. The estimated S-N curves are compared to the FAT curves proposed by IIW-HFMI [6], EC3 [11] and DNV GL [12].

4.2 HFMI-treated butt welds

The results of the test series on butt welds and the respective characteristic fatigue strengths are presented in Fig. 4 and Table 4 respectively. HFMI treatment leads to a significant increase in fatigue strength (95% survival probability). Fatigue strength values from 182 MPa up to 237 MPa were achieved even under the influence of the investigated corrosive environments. For the series BW_HFMI_SSC_b and S_HFMI_ASW_b with specimens tested under 4-point bending load, the number of cycles was higher for the same stress levels in comparison to the axial tested specimens of the series BW_HFMI_SSC_ax. The BW_HFMI_SSC_b series also provides higher characteristic values than the BW_HFMI_ASW_b series. The calculated fatigue strength values (mean and 95%-interval for survival) confirm this tendency. Due to the HFMI treatment, the failure of the BW_HFMI_SSC_b and BW_HFMI_ASW_b series, which are subjected to bending stress, is shifted from the weld toe to the corroded parent material for all specimens. The scatter of the test results is low for the failure in the base material, despite the influence of bending stress. For the parent material, artificial seawater seems to have a more severe influence on fatigue strength than pre-corrosion by salt spray. Since the application of dye penetrant tests on these specimens showed no crack formations in the area of the weld toes, these results are used as the lower limit for calculating the fatigue strength.

In order to consider the influence of the loading type on fatigue life, characteristic fatigue strength value determined by bending is reduced by the correction factor k_{tb} according to BS 7608 [19]. The correction factor is calculated to k_{tb} = 1.31 for the investigated weldment with main plate thickness t = 15 mm. The modified value $\Delta\sigma_{c,95\%,ax\text{-}mod}$ = 163 MPa results from a calculated reduction by its reciprocal value to 76% of the fatigue strength under bending. In this case, the calculated value is below the fatigue strength of the series BW_HFMI_SSC_ax tested under axial tensile load. Conservatively, the series BW_HFMI_ASW_b,ax-mod with the modified fatigue strength of 163 MPa is used as a basis for the design proposal. Thus, the fatigue strength of HFMI-treated corroded butt welds is above the design recommendation of 160 MPa for uncorroded HFMI-treated butt welds according to IIW [6]. For this reason, FAT class 160 is also proposed for the corroded HFMI-treated butt welds. The derived design proposal is thus five FAT classes higher than the FAT 90, which is applicable for uncorroded, as-welded joints according to EC3 [11]. A FAT class assignment of eight classes higher than in the case of as-welded butt welds, which are exposed to free corrosion and are classified as FAT 63 according to DNV GL [12], is recommended. It is becoming evident that even in corrosive environments, the HFMI treatment can significantly increase the fatigue strength of butt weld joints.

4.3 HFMI-treated non-load-carrying transverse attachments

The test results of the respective series of transverse attachments and their estimated fatigue strengths are presented in Fig. 5 and Table 4 respectively. The HFMI treatment leads to a significant improvement of the characteristic fatigue strength (95% survival probability) to values from 130 MPa up to 134 MPa for the investigated cases of laboratory corrosion. Transverse attachments were mainly fractured in the area of the weld toe. The results of the series, which were tested under bending load, TA_HFMI_ASW_b and in particular TA_HFMI_SSC_b show a significantly larger scatter compared to the series TA_HFMI_SSC_ax, whose specimens were tested under axial tensile load. Due to this large scatter and the small sample of the TA_HFMI_SSC_b series, no conclusive evaluation of the characteristic fatigue strength is possible (value written in grey and italics). Despite the positive effect of bending load on the mean fatigue strength, the transverse attachments of the test series TA_HFMI_ASW_b subjected to bending in artificial seawater show lower mean values and lower 95%-interval values than the series TA_HFMI_SSC_ax, which were dry-tested subsequently to pre-corrosion in the salt spray chamber. The reduction of the fatigue strength is decisively influenced by the acceleration of the crack growth phase due to the simultaneous corrosion during the fatigue test [2]. This is particularly evident with specimens that account for a large number of cycles during the crack growth phase (testing at a low stress level).

Due to the larger scatter of the results for the series tested under bending, the characteristic fatigue strength is in the range of the series of specimens tested under axial tensile load. This is in agreement with previous investigations by Maddox [20], which have shown no significant influence of the loading mode on the characteristic fatigue strength of as-welded transverse attachments. Therefore, no modification of the fatigue strength due to the loading type is adopted in the case of transverse attachments.

The characteristic fatigue strength of the TA_HFMI_ASW_b series, which have been tested in artificial seawater, lies at 130 MPa below the 134 MPa characteristic fatigue strength of the TA_HFMI_SSC_ax series and is therefore adopted as the reference S-N curve. The data points of all series lie above the S-N curve of this FAT class and above the FAT 140 recommended in [6] for uncorroded, HFMI-treated transverse attachments. Nevertheless, due to the statistical evaluation of the characteristic fatigue strength this FAT 140 is not accomplished.

FAT 125 is conservatively recommended based on the reference FAT class of the test series TA_HFMI_ASW_b. This corresponds to a reduction by one FAT class compared to the IIW recommendations for HFMI due to the influence of corrosion. As for the butt welds, the slope of the design curve m is set equal to 5 according to IIW [6].

Despite the reduction by one FAT class in comparison to the recommendations by IIW [6] for uncorroded and HFMI-treated transverse attachments, the recommended FAT 125 still lies four FAT classes higher than the specifications of EC3 [11] with FAT 80 for as-welded joints. Furthermore, the resulting FAT 125 is significantly higher than FAT 56, which according to DNV GL [12] has to be adopted for as-welded transverse attachments under free corrosion. Similar to the butt welds, investigations regarding transverse attachments show that a considerable improvement in fatigue strength can be achieved by HFMI treatment.

5 Conclusion and outlook

Fatigue tests on corroded weldments have shown that the use of high frequency mechanical impact treatment can lead to a significant increase of their fatigue strength, even when exposed to corrosive environments, as long as no substantial thickness loss ($\Delta d > 0.1$ mm) occurs due to corrosion. This could be validated for the investigated laboratory corrosion methods of deposition in the salt spray chamber and in artificial seawater. Based on the experimental results, recommendations for the design of HFMI-treated butt welds and transverse attachments were developed considering the described corrosive environments. The corroded butt welds are assigned to FAT 160 and the corroded transverse attachments are classified as FAT 125. The slope of the S-N curves is assumed as m = 5 for both cases.

Within the scope of further investigations, the long-term corrosion behaviour shall be considered taking into account a larger plate thickness loss. In addition, further analyses of the influence of notch sharpness and thickness effects are planned.

Literature

[1] BSH-Nr. 7005 "Standard Konstruktion – Mindestanforderungen an die kownstruktive Ausführung von Offshore-Bauwerken in der ausschließlichen Wirtschaftszone (AWZ)". Bundesamt für Seeschifffahrt und Hydrographie, Hamburg 2015.

[2] Ummenhofer, T., u. a.: Erhöhung der Ermüdungsfestigkeit von Offshore-Windenergieanlagen durch Schweißnahtnachbehandlung unter Berücksichtigung des Korrosionseinflusses [Increase of fatigue strength of offshore wind energy power-plants through post-weld treatment in consideration of corrosion influence]. Final report. Research project IGF-Nr.: 18.457 N / DVS-Nr.: 09.069. Karlsruhe, München 2018.

[3] Gkatzogiannis, S., et al.: Correlation of laboratory and real marine corrosion for the investigation of corrosion fatigue behaviour of steel components. International Journal of Fatigue 126 (2019), pp. 90/102. https://doi.org/10.1016/j.ijfatigue.2019.04.041.

[4] Weinert, J., et al.: Application of high frequency mechanical impact treatment to improve the fatigue strength of welded joints in corrosive environment. IIW-XIII-2781-19, 72nd IIW Annual Assembly and International Conference, Bratislava, Slovakia 7-12 July 2019.

[5] Hobbacher, A.: Recommendations for fatigue design of welded joints and components. 2nd edition. Springer International Publishing, Cham 2016.

[6] Marquis, G. B., Z. Barsoum: IIW Recommendations for the HFMI Treatment: For improving the Fatigue Strength of Welded Joints (IIW Collection). 1st edition. Springer Singapore, Singapore 2016.

[7] Weinert, J., et al.: Erhöhung der Ermüdungsfestigkeit von geschweißten Konstruktionsdetails in korrosiver Umgebung durch Anwendung höherfrequenter Hämmerverfahren. Schweißen und Schneiden 70 (11), 2018, pp. 782/89.

[8] Kuhlmann, U., et al.: Effizienter Stahlbau aus höherfesten Stählen unter Ermüdungsbeanspruchung [Fatigue strength improvement for welded high strength steel connections due to the application of post-weld treatment methods]. Forschung für die Praxis P620, Forschungsvereinigung Stahlanwendung e. V. (FOSTA). Verlag und Vertriebsgesellschaft mbH, Düsseldorf 2006.

[9] Ummenhofer, T., et al.: REFRESH – Lebensdauerverlängerung bestehender und neuer geschweißter Stahlkonstruktionen. Forschung für die Praxis P702, Forschungsvereinigung Stahlanwendung e. V. (FOSTA). Verlag und Vertriebsgesellschaft mbH, Düsseldorf 2011.

[10] Yildirim, H. C., G. B. Marquis: Overview of fatigue data for high frequency mechanical impact treated welded joints. Welding in the World 56 (2012), Issue 7/8, pp. 82/96.

[11] DIN EN 1993-1-9 "Eurocode 3: Bemessung und Konstruktion von Stahlbauten – Teil 1-9: Ermüdung" (Edition December 2010).

[12] DNVGL-RP-C203 "Fatigue design of offshore steel structures" (Edition April 2016).

[13] DIN EN 10025-2 "Warmgewalzte Erzeugnisse aus Baustählen – Teil 2: Technische Lieferbedingungen für unlegierte Baustähle" (Edition April 2005).

[14] DIN EN ISO 9227 "Korrosionsprüfungen in künstlichen Atmosphären – Salzsprühnebelprüfungen" (Edition July 2017).

[15] ASTM D1141-98 "Standard practice for the preparation of substitute ocean water" (Edition January 2013).

[16] Oberparleiter, W.: Einfluss von Prüffrequenz und Salzgehalt des Korrosionsmediums auf die Korrosionsermüdung von Stählen bei betriebsähnlichen Lastabläufen. Werkstoffe und Korrosion 37 (1986), Issue 7, pp. 391/97.

[17] Weich, I.: Ermüdungsverhalten mechanisch nachbehandelter Schweißverbindungen in Abhängigkeit des Randschichtzustands. Diss., TU Braunschweig 2009.

[18] Euler, M., U. Kuhlmann: Statistical intervals for evaluation of test data acc. to Eurocode 3 Part 1-9. 3rd draft. Contribution to Working Group 6.3: Statistical Analysis of Fatigue Data ECCS Technical Committee 6 – Fatigue. Stuttgart 2014.

[19] BS 7608 "Guide to fatigue design and assessment of steel products" (Edition March 2014).

[20] Maddox, S. J.: Allowance for bending in fatigue design rules for welded joints. IIW-XIII-2580-15, 2015.

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